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# Earth Grounding Beds—Design and Evaluation

Proceedings: Bureau of Mines Technology Transfer Seminars, Pittsburgh, PA, June 25, 1985, and Reno, NV, June 27, 1985

Compiled by Staff, Bureau of Mines

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
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BUREAU OF MINES
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## PREFACE

This publication both complements and supplements Bureau of Mines Information Circular 8767, "Cuide for the Construction of Driven-Rod Ground Beds." The soil resistivity and bed resistance measurement procedures referenced herein are fully explained in IC 8767. It is recommended that the reader be familiar with both documents before designing a ground bed. Together, they will facilitate the selection of the best types of bed (rod, borehole, or composite) for a particular application.

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CONTENTS


| | Page |
|---|---|
| Preface | i |
| Abstract | 1 |
| Introduction | 2 |
| Guide for the construction of borehole ground beds, by H. W. Hill, Jr. | 3 |
| Composite ground beds for high-resistivity soils, by M. R. Yenchek | 8 |
| Procedure for the direct measurment of touch potentials, by W. L. Cooley, H. W. Hill, Jr., and M. L. McBerry | 12 |
| References | 24 |


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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| A | ampere | m | meter |
| ft | foot | mA | milliampere |
| $ft^2$ | square foot | ohm-ft | ohm-foot |
| Hz | hertz | pct | percent |
| in | inch | V | volt |
| kV | kilovolt | V/A | volt per ampere |

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ABSTRACT

Recent Bureau of Mines research in earth grounding safety is documented in three separate papers. First, guidelines for the design of a 5-ohm borehole ground are presented. Next, an inexpensive practical means to construct a low-resistance bed in high-resistivity soil is described. Finally, a procedure that employs a commercial resistivity meter to measure shock potentials around grounded objects is explained step-by-step. These papers complement the material presented at an earlier technology transfer seminar and published as IC 8767.

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## INTRODUCTION

It has been established that the resistance of mine ground beds should be designed as low as practical, with 5 ohms as a generally acceptable value (1-2).[1] Step-by-step procedures for designing a 5-ohm, driven-rod bed are documented in a Bureau of Mines Information Circular (IC 8767) (3). However, in certain cases, the driven-rod bed may not be the best choice for maximum protection or cost effectiveness.

For instance if land area is limited or if step and touch potentials are a prime concern around the surface substation, an existing borehole may be more suitable as the earth electrode than a driven rod. Further, if soil resistivity exceeds 500 ohm-ft, a rod bed may be impractical from an economic standpoint. In such a case a composite bed utilizing low-resistivity fill may be the best option.

Consequently, one of the purposes of this publication is to guide the bed designer in selecting the most appropriate bed type for each particular situation, given the options of driven rods, an existing borehole, or composite materials. The papers by Hill and Yenchek, reporting on borehole and composite ground beds, respectively, act as a supplement to IC 8767, which covers the driven-rod option.

Once a ground bed has been constructed, its resistance has traditionally been the gauge for the safety of the entire grounding system. However, recent Bureau research has shown that mine grounding systems may pose dangers to personnel under certain conditions, despite a low bed resistance. These hazards may arise during phase-to-earth faults and take the form of dangerously high step and touch potentials around grounded equipment at locations remote from the substation.

In the final paper from this seminar, Cooley, Hill, and McBerry explain a new method for evaluating these potential hazards without interfering with mine operations. As such, this paper serves as a complement to IC 8767 and the first two papers in this publication.

[1]Underlined numbers in parentheses refer to items in the lists of references at the end of the final paper in this report.

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# GUIDE FOR THE CONSTRUCTION OF BOREHOLE GROUND BEDS

By H. W. Hill, Jr.[2]


## ABSTRACT

Using the resistivity measurement techniques of IC 8767 (3), this guide is intended to help the user decide between a ground bed constructed from rods and one consisting of a borehole. Cost and safety issues for both types of beds are discussed. For the engineer who decides to build a borehole ground, design tables are included for a 5-ohm ground bed in earth of various resistivities. Design verification procedures are given that are tailored for the borehole ground bed.


## INTRODUCTION

The construction of any ground bed is not an exact procedure. Two formidable obstacles keep the design methods from being exact: the complex ways that current and voltage vary within the earth and the practical difficulties of determining the earth resistivity in sufficient detail to determine these variations. To accurately predict the resistance of a ground-bed design, the electrical resistivity of every cubic inch of earth at the proposed site should be known. These millions of values (that can only be obtained from surface measurements) must be then used in a mammoth computer program to precisely predict the resistance of the completed bed.

These limitations have more significant implications for borehole ground beds than for rod beds, because the resistivity is easily measured only at the earth's surface. Consequently, more information is available about the resistivity near the surface than at great depths (although interpretation of surface measurements yields some estimates of subsurface resistivity). Borehole ground beds extend farther beneath the surface and thus depend more on the subsurface resistivity than rod beds. The end result is that the design procedures and tables presented here for borehole beds are NOT as dependable as those for driven-rod beds in IC 8767, so that a conservative design philosophy is even more important.

## CHOOSING BETWEEN BOREHOLES AND DRIVEN RODS

Either boreholes or driven rods can serve equally well as the basis of a satisfactory ground bed in most installations. However, there are special situations for which one or the other is a far superior choice. This section addresses some of those situations.

### Installations With Existing Boreholes

A mine with existing borehole(s) should consider the impact that these borehole(s) have on the mine safety grounding system, even if they are not presently connected to the grounding system, and whether or not the existing grounding system is adequate. This is particularly true of underground mines, where (for instance) boreholes may be used to supply power to rail haulage at various points, or where metal water lines make their way out of the mine at different locations. The fact is that these pipes and borehole casings are capable of transferring voltages from the surface to underground, regardless of their reason for existence.

This subject is discussed in some detail in Bureau IC 8835, "Guide to Substation Grounding and Bonding for Mine Power Systems" (4). The basic consideration is that adequate protection from electrical shock cannot be provided to personnel at both ends of a borehole casing. Borehole casings within a substation should be connected to the substation ground and avoided by personnel underground. Boreholes more than 50 ft from the substation can be connected to the safety ground system. If boreholes are not connected

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to the grounding system in any way, personnel should avoid contact with them.

### New Installations and Installations With Excessive Bed Resistance

When a new ground bed must be built, either for a new installation with no existing bed or in an older installation with a seriously deficient ground bed, concerns for safety should have the highest priority in picking the type of bed to be built. The most important safety advantages and disadvantages of borehole ground beds relative to driven-rod beds are discussed below.

#### Advantages

1. Lower standard touch potentials on the surfaces: The potential around a borehole electrode (carrying ground-fault current) decreases logarithmically with the distance from the borehole, whereas the potential around a rod bed decreases with the reciprocal of distance. The latter variation is more dramatic, causing higher differences in voltage. Figure 1-1 illustrates this difference between bed types.

2. Capable of achieving lower resistance: For a given fault current, the lower the ground-bed resistance, the lower the fault voltage will be. Therefore, a borehole is safer if it yields a lower resistance. Because the resistance of a borehole depends on subsurface resistivity that may be significantly lower than surface resistivity, a borehole ground bed may have a lower resistance than a rod bed.

3. Less seasonal variation in resistance: Soil has a substantially higher resistivity when it freezes. Boreholes typically extend far beneath frost penetration depths, so the resistance does not change as radically in winter as does the resistance of rod beds.

#### Disadvantages

1. Higher step and touch potentials underground: When fault current flows from a ground bed into the earth, the ground near the bed becomes elevated in potential almost to the same extent as the bed itself. Because the borehole extends deeper into the ground than do other bed types, voltages are transferred deeper underground also.

2. Less lightning protection than rod beds: Although lightning may strike a borehole casing, particularly in high-resistivity soil, lightning currents will typically not be conducted down a long borehole casing if they first strike another conductor connected to the borehole. This can be interpreted to mean that the ground bed has a higher resistance to lightning than a rod bed, even though the rod bed may measure the same or higher resistance in a test.

3. More difficult to design and measure adequacy: Ground-bed design is no more accurate than the resistivity data on which it is based. Borehole design requires subsurface resistivity data that typically are not well known.

4. Joints in casings can suddenly increase resistance: Borehole casings used as grounds can be treacherous, because joints between sections may not provide a good electrical contact. Often, newly constructed boreholes will provide electrical continuity from end to end, but this continuity will not be maintained as the borehole ages. Frequent measurement is recommended for this type of ground bed.

### Cost Advantages and Disadvantages of Borehole Grounds

If there is no clear choice on the basis of safety for picking boreholes or

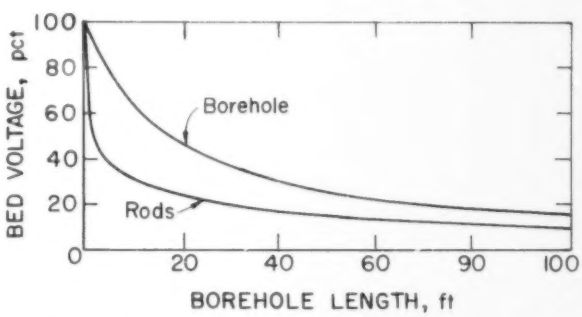


FIGURE 1-1. - Bed voltage versus distance.

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driven rods, the cost issue should be examined. The advantages and disadvantages of boreholes in terms of cost are summarized below.

Advantages

1. Less real estate committed to borehole ground bed: Obviously, it takes less surface area for one borehole casing than it does for a bed of driven rods, since each rod must be separated by practical distances from one another. However, this advantage is somewhat offset by the fact that the voltage is higher between a borehole ground and any other ground bed than between driven rods and any other ground bed. Therefore, for safety reasons a borehole ground must be placed farther from the substation than a bed consisting of driven rods. Figure 1-1 quantifies this necessary difference in required spacing; for example, with a maximum voltage of 50 pct the nearest rod may be only a few feet from the substation, whereas a borehole would have to be about 20 ft away. (The coupling between beds is identical to the voltage shown on the vertical axis.)

2. Less material if subsurface resistivity is low: The amount of material necessary to construct a ground bed of a given resistance is directly proportional to the resistivity of the earth in contact with the bed. If the subsurface resistivity is substantially lower than the surface resistivity, a borehole ground extending into this lower resistivity region may require less material than a rod bed on the surface.

Disadvantages

1. The borehole construction technique is more expensive per electrode than the driven-rod techniques.

2. Elaborate methods are necessary to assure earth contact.

Both disadvantages are consequences of the differences in construction between boreholes and rod beds. Because the rods are driven into the earth, no hole has to be made for them in advance. Also, because the rod is forced into the earth, the contact between the earth and the rod tends to be quite good.

If, after reviewing the safety and cost factors listed above, the borehole remains a viable choice, then a borehole ground can be designed using the method outlined in the next section. After comparing this borehole design with a rod bed design (using IC 8767), a final decision can be made.

DESIGN OF A BOREHOLE GROUND BED

Design of any ground bed begins with measurements of earth resistivity. It is recommended that the borehole ground bed design begin with the same resistivity measurements that are detailed on pages 10-13 and illustrated in figures A-1 through A-4 of IC 8767. Particular attention should be paid to the results of measurement B and measurement D. The lower these numbers are relative to measurements A and C, the more suitable[3] the proposed site is for a borehole ground. Of course, a borehole ground bed can be constructed even if measurements A and C yield lower resistivities than the other tests.

The preliminary design is carried out by averaging the resistivities obtained in measurement B and measurement D. This average value is used with table 1-1 to obtain the tentative dimensions of a borehole ground.

If the average resistivity falls between two values in the table, the higher value should be used. For example, if measurement B yielded 550 ohm-ft and measurement D yielded 470 ohm-ft, the average is 510 ohm-ft, so the line in the table corresponding to 700 ohm-ft should be used. Any one of the combinations of borehole length and diameter in table 1-1 should be satisfactory, except those marked with asterisks, which are shown for illustrative purposes only. Choice among the alternatives here can be made on the basis of available materials and/or existing boreholes.

[3]More suitable here means more efficient use of material.

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TABLE 1-1. - Minimum borehole lengths for a 5-ohm bed, feet

| Minimum | Maximum earth resistivity, ohm-ft | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| diameter, in | 100 | 200 | 300 | 500 | 700 | 1,000 | 2,000 | 3,000 |
| 1 | 22 | 49 | 79 | 140 | 205 | 305 | 660 | 1,032 |
| 2 | 20 | 44 | 71 | 128 | 187 | 281 | 611 | 959 |
| 4 | 17 | 29 | 63 | 115 | 170 | 256 | 561 | 885 |
| 6 | 15 | 36 | 59 | 108 | 159 | 241 | 532 | 842 |
| 8 | 14 | 34 | 55 | 102 | 152 | 230 | 511 | 811 |
| 12 | 12 | 31 | 51 | 94 | 141 | 215 | 481 | 767 |
| 16 | 11 | 28 | 47 | 89 | 134 | 204 | 460 | 735 |
| 20 | 10 | 26 | 45 | 85 | 128 | 196 | 444 | 711 |
| 24 | [1]9 | 25 | 42 | 81 | 123 | 189 | 430 | 690 |
| 30 | [1]8 | 23 | 40 | 77 | 116 | 180 | 413 | 666 |

[1]Questionable values because they are beyond the range of validity of underlying assumptions.

The second step in the design is to carry out additional resistivity measurements, with electrode spacings as close as practical to the length of the chosen borehole in table 1-1. If the borehole chosen has a length of 25 ft or less, this step can be omitted because measurements B and D were done with 18-ft spacings. If the electrode spacings cannot be increased to the specified borehole length, then the maximum electrode spacings should be used. The measurement taken along the same baseline as measurements A and B will be referred to as measurement E; the new measurement made perpendicular to the baseline (that is, the same line as measurements C and D) will be referred to as measurement F.

Making measurements E and F with shorter spacings than the borehole length will introduce more error into a process that is already uncertain; the final design should be made more conservative (longer borehole, larger diameter) if the measurements must be made with short spacings. The larger the discrepancy between measurements E and F and measurements B and D, the more uncertainty there is.

If the results of measurement E and F are within 20 pct of each other, then the average of these results should be used to pick a new design from table 1-1. Otherwise, the larger of the two results should be used. Hopefully, this design will be the same as the initial one chosen above. However, if the results of these latter measurements are very different from measurements B and D, the same design cannot be used.

If the borehole length in the new design differs by more than 20 pct from the length in the first design, the possibility of making more resistivity measurements should be considered. This is particularly important if the new design calls for a longer length than the initial design, and the maximum possible electrode spacing was NOT used in measurements E and F. The results of the repeated measurements should be used in picking a third design (that, hopefully, will be the same as the second design).

## DESIGNING A BOREHOLE GROUND FOR OTHER THAN 5 OHMS

Table 1-1 was computed for 5-ohm ground beds, because the majority of safety ground beds are designed for this value. However, the table can also be used for other design values. The procedure is very similar to the one described in IC 8767. Each measured resistivity is divided by the fraction of 5 ohms represented by the desired ground-bed resistance. If measurements B and D yield an average of 400 ohm-ft, and a 4-ohm ground bed is desired, the 400 ohm-ft must be divided by 4/5. Table 1-1 would then be used with the "fictitious" value of 500 ohm-ft. (The same procedure would be followed with the results of measurements E and F.)

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## MEASUREMENT OF BOREHOLE RESISTANCE

Once the ground bed is designed and built, its resistance must be measured to ensure that the desired resistance value has been achieved. Ground-bed resistance measurement is described in detail in IC 8767, pages 4-6. It is illustrated in figure 4 of that publication, with sample results shown in figure 5. The primary concern in measuring the resistance of a borehole ground is to locate the auxiliary current electrode at a sufficient distance (D) from the borehole. Preferably, the current electrode should be placed more than five borehole lengths from the borehole. In this case, the procedure described in IC 8767 can be used without modification to find the resistance of the borehole ground.

Because borehole lengths are typically on the order of several hundred feet, frequently the current electrode cannot be placed 5 times this distance from the ground bed. Equipment limitations and unfavorable terrain are the most common constraints on electrode placement. The fall-of-potential measurement procedure must be modified if the current electrode is to be placed closer than specified above.

The current electrode should be positioned at a distance, D, that corresponds to one of the positions in table 1-2; that is, it should be located either at 1/2, 2/3, 1 or 2 borehole lengths from the borehole. For any of these positions, the fall-of-potential measurement is carried out as specified in IC 8767, but the potential-electrode position used for the resistance determination is not 0.618 times the current-electrode spacing (as given in IC 8767) but rather the fraction indicated in table 1-2 times the current-electrode spacing. The smaller the current-electrode spacing used, the more questionable is the resistance measurement.

TABLE 1-2. - Potential-electrode location for borehole resistance measurement

| Current-electrode position:[1] | Potential-electrode position[2] |
|---|---|
| 2..... | 0.602 |
| 1..... | .570 |
| 2/3..... | .538 |
| 1/2..... | .509 |

[1]Multiple of borehole length.
[2]Fraction of distance (D).

## CONCLUSION

This paper has expanded but not replaced the content of IC 8767 to provide the user with additional choices for designing and building a ground bed. The discussion presented here of advantages and disadvantages of borehole grounds should foster an intelligent choice of grounding technique. The material presented on ground-bed measurement will enable the user to verify the adequacy of a chosen design.

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# COMPOSITE GROUND BEDS FOR HIGH-RESISTIVITY SOILS

By M. R. Yenchek[4]


## ABSTRACT

An inexpensive, practical means to construct a low-resistance ground bed where soil resistivity exceeds 500 ohm-ft is described. The technique involves using a large quantity of semiconducting fill material in contact with a relatively small, metal-grounding electrode. This composite material bed is shown to be superior to conventional rod beds from both safety and economic standpoints. The design of a 5-ohm, circular-ring composite bed is explained step-by-step, beginning with soil resistivity measurements and ending with a check on bed resistance. The resistivities of fill materials commonly found near mine sites are listed.


## INTRODUCTION

The earth connections of power distribution systems, typically ground beds, protect personnel and equipment from many operational hazards. A properly designed bed exhibits low resistance to limit the potentials of the metallic frames connected to it and to facilitate activation of ground-fault protective devices. In addition, it minimizes voltage gradients during lightning strikes and phase-to-earth faults.

Many mining sites are located in dry, rocky terrain where the soil exhibits high resistivity; values greater than 3,000 ohm-ft have been measured (5). Since bed resistance is directly proportional to soil resistivity, construction of a low-resistance ground bed by conventional methods may be difficult in these areas. For example, to build a 5-ohm, driven-rod bed in 3,000 ohm-ft soil requires one hundred 10-ft rods distributed over 5-1/2 acres (3). A bed of this magnitude is not only expensive but very impractical. Even if such a bed were to be constructed, dangerous potentials from fast-rise-time wavefronts, i.e., lightning, would be likely when the bed would conduct current.

What is needed is an inexpensive, practical means to construct a low-resistance ground bed in high-resistivity soils. An alternative to using only metal as the grounding electrode would be to use a large quantity of an inexpensive, low-resistivity, semiconducting material in contact with a relatively small metal electrode. This fill and metal-electrode combination comprises a composite ground bed. This paper shows that such a design can be superior to conventional rod beds in high-resistivity soils.

## ADVANTAGES OF THE COMPOSITE GROUND BED

A composite ground bed can take many shapes. If there is a natural depression at the proposed site, fill can be dumped into it to cover the metallic electrodes; on level ground the fill can be mounded. The grounding electrodes can be vertical rods or horizontal conductors.

One practical composite design in the form of a circular ring is shown in figure 2-1. Here a copper conductor (typically 1/0 to 4/0 AWG) is buried in contact with a low-resistivity fill material. The advantages of a composite bed become apparent if we analyze the circular ring configuration in 1,000-ohm-ft soil.

We can achieve a 5-ohm bed resistance by constructing a circular composite bed using low-resistivity material from a sanitary landfill. The radius of the fill material surrounding the metal conductor need only be about 2.5 ft and the metallic ring radius about 60 ft. In contrast, the radius of a 5-ohm wire ring directly buried in 1,000-ohm-ft soil must be over 100 ft (6).

[4]Electrical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

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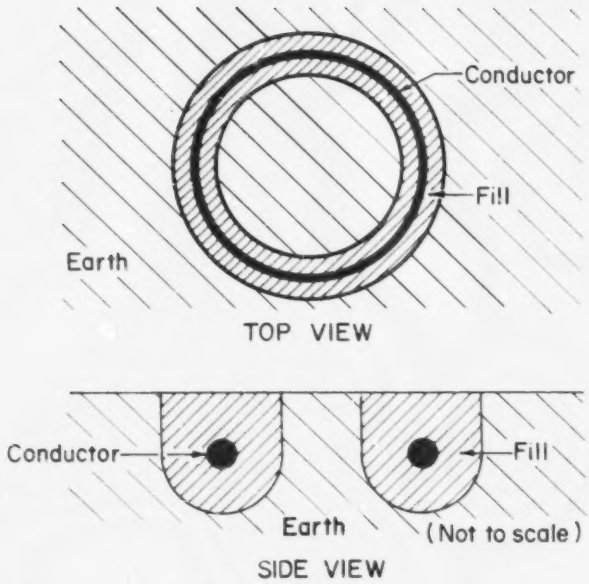


FIGURE 2-1. - Circular ring composite ground bed.

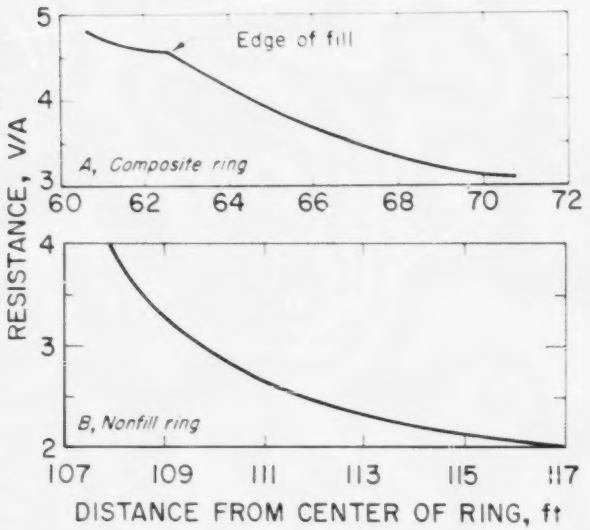


FIGURE 2-2. - Voltage profiles for composite and nonfill ring designs.

The effect of the composite fill material is more striking when the voltage profile of the surrounding earth is examined. This effect is shown in figure 2-2 for both the composite and nonfill ring designs (6). The profile slope is an indication of the severity of the potentials associated with the bed during current flow through the earth--the steeper the slope, the greater the shock hazard to personnel near the bed. Notice that the profile for the nonfill bed has a steeper slope particularly near the metal ring.

Thus, the use of fill materials reduces the magnitude of voltage gradients near the bed. For the examples in 1,000-ohm-ft soil, it can be shown that gradients near the composite bed are one-half those near the nonfill bed (5).

The costs of installing a ground bed must include the costs of excavation and materials. Excavation costs are incurred for both the composite and nonfill designs. The composite bed is economically feasible if low-resistivity fill is available near the bed site. Generally, if fill costs including transportation can be limited to less than 6 times the costs of the ring excavation, a composite bed is a good choice (6).

## COMPARISON WITH CONVENTIONAL ROD BEDS

To build a 5-ohm bed using metallic rods in 1,000-ohm-ft soil, a 9 by 9 array of 8-ft rods (81 rods) spaced as in figure 2-3 is required (6). The greatest voltage gradients under fault conditions would occur around the bed perimeter [1.78 V/A of fault current (6)]. As the vertical rods must be interconnected horizontally, excavation costs are significant and, generally, far exceed the cost of the rods. The horizontal interconnections reduce bed resistance by only 15 pct, so the overall bed size would not change appreciably (7).

This 5-ohm rod design for 1,000-ohm-ft soil is compared with the circular-ring composite bed design in table 2-1 (5). Note that the composite bed requires more land than the rod bed. This drawback is offset by the fact that a composite circular-ring ground may be constructed at a much lower cost if low-resistivity fill is readily available. More importantly, the maximum potentials associated with a rod bed are nearly three times those of the composite design, an important consideration in substation design. So, for high-resistivity soils the composite circular ring is a realistic alternative.

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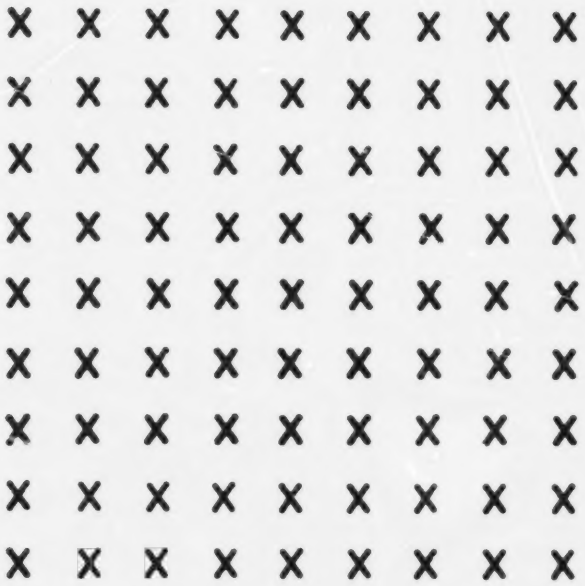

$\rho$ = 1,000 ohm-ft
Rod length = 8 ft
Rod radius 0.0208 ft
81 rods
12.7-ft rod spacing

FIGURE 2-3. - Driven-rod ground bed.

TABLE 2-1. - Comparison of conventional rod and composite ring beds

| | Ground area, $ft^2$ | Maximum gradient, V/A |
|---|---|---|
| Conventional rod bed..... | 10,404 | 1.78 |
| Composite circular ring.... | 14,400 | .77 |

## RESISTIVITIES OF COMMON FILL MATERIALS

The fill material used in a composite ground bed must be inexpensive and should have a resistivity less than 200 ohm-ft. Fill materials commonly found near mine sites are given in table 2-2 (6). For a given bed resistance, the lower the fill resistivity, the smaller the bed dimensions.

TABLE 2-2. - Resistivities of common fill materials

| | Resistivity, ohm-ft |
|---|---|
| Waste coal pile..... | 100 |
| Sanitary landfill.... | 10-45 |
| Steel-mill slag pile. | 150 |
| Garden soils..... | 15-160 |

## DESIGN OF A COMPOSITE GROUND BED

The resistance of the composite circular-ring ground bed (6) is given by--

$$R_\infty = \frac{\rho_2}{2\pi^2 r}\left[\ln \frac{8r}{a} - \ln \frac{8r}{a_f}\right] + \frac{\rho_1}{2\pi^2 r} \ln \frac{8r}{a_f} \qquad (1)$$

where $R_\infty$ is the bed resistance with respect to infinite earth,

$\rho_1$ is the earth resistivity,

$\rho_2$ is the fill resistivity,

$a_f$ is the fill radius,

$a$ is the metallic conductor radius,

and $r$ is the ring radius.

This expression was analyzed for various earth and fill resistivities assuming a 2/0 conductor and $R_\infty$ set at 5 ohms. The results are graphed in figure 2-4 for reference in the design process.

Generally the composite bed design is a good choice if--

- soil resistivity exceeds 500 ohm-ft,
- sufficient land area is available, and
- low-resistivity fill is nearby.

The design of any ground bed begins with soil resistivity measurements. The procedure detailed in IC 8767 should be referenced for the discussion below.

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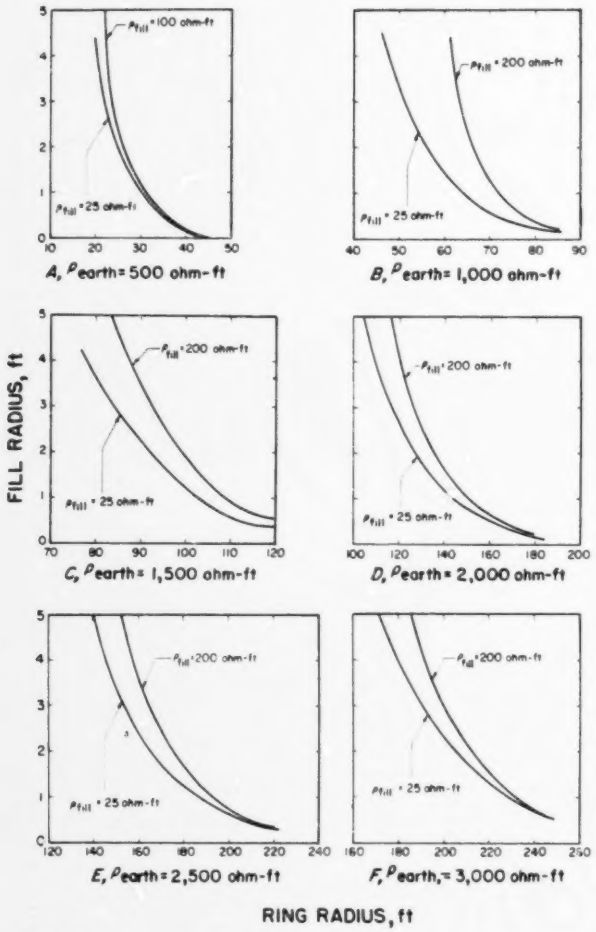
A, ρearth = 500 ohm-ft
B, ρearth = 1,000 ohm-ft
C, ρearth = 1,500 ohm-ft
D, ρearth = 2,000 ohm-ft
E, ρearth = 2,500 ohm-ft
F, ρearth = 3,000 ohm-ft
FILL RADIUS, ft
RING RADIUS, ft

FIGURE 2-4. - Radii required for earth resistivity.

If all four resistivity readings are within 20 pct of each other, figure 2-4 (6) may be used directly without restrictions. Simply look up the nearest earth and fill resistivities and determine the appropriate ring and fill radii.

If the baseline resistivity measurements A and B (3) are close and the measurements perpendicular to the baseline (C and D) are close, but differ from A and B, then the dimensions of the composite ring should be modified to an ellipse shape with the axes proportional to the ratio $(\rho_A + \rho_B)/(\rho_C + \rho_D)$. For example, if the average resistivity along the base line is 1.5 times the average perpendicular to the baseline, the radius of the ring should be increased by 50 pct along the baseline.

If the resistivity readings at 6-ft spacings (A and C) (3) are close to each other, but differ from the 18-ft readings (B and D), the average of readings A and C should be used in figure 2-4.

If no more than two of the resistivity measurements are close (less than 20 pct apart), then the baseline should be moved 45° clockwise or counterclockwise and all four measurements repeated. If these numbers differ by more than 20 pct, then the highest of the four resistivity measurements, not the average, should be used when referencing figure 2-4.

## MEASUREMENT OF THE COMPOSITE BED RESISTANCE

Once the composite bed has been designed and built, its resistance should be measured using the fall-of-potential procedure described in detail in IC 8767 and other grounding handbooks (3, 8). The current electrode should always be located at least a distance of 10 times the ring radius from the center of the ring. The bed resistance should be the reading obtained when the potential electrode is about 60 pct of the distance to the current electrode (9).

## CONCLUSION

This paper has shown how to construct a practical, low-resistance ground bed in high-resistivity soils. This composite design utilizes a large quantity of low-resistivity fill in contact with a metal electrode. It is presented as an alternative to conventional driven-rod beds and is particularly advantageous if suitable fill material is readily available.

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# PROCEDURE FOR THE DIRECT MEASUREMENT OF TOUCH POTENTIALS

By W. L. Cooley,[5] H. W. Hill, Jr.,[6]
and M. L. McBerry[7]

## ABSTRACT

The procedure outlines a method by which the personnel safety provided by a mine grounding system can be estimated in a direct way. Actual touch potentials, resulting from a small-scale simulated fault, are measured. Because it does not require that the ground bed be disconnected, the procedure avoids the need to interrupt mine production while ground system safety is determined, and it provides an assessment of the effectiveness of the entire ground system, not just the isolated ground bed itself.

The measurements needed are relatively simple, requiring the use of a four-electrode earth resistance meter, which is insensitive to any stray ground current that may be flowing in the area. Hazardous touch potentials could occur at thousands of points throughout the mine property. The bulk of the detail given in the procedure provides a straightforward method of identifying those few areas on the mine property where the most hazardous touch potentials are likely to occur, and gives step-by-step instructions for the verification of these points and the estimations of the potentials that could occur there under fault conditions. It guides the user through the interpretations of the results and suggests ways in which hazards can be reduced.

## INTRODUCTION

Personnel making electrical measurements on power systems are always subject to some risk of electrical shock. Any metal object or wire connected to a power system should be assumed to be lethal until it has been tested for voltage. The grounding system is not an exception to this rule. People have been shocked by ground beds.

Neither the ground-bed resistance method nor the technique described here tests the ability of the grounding conductors to carry the high currents of a phase-to-ground fault. Additional physical inspections or high-current tests should be performed to verify that the grounding system can carry these currents. The magnitude of possible fault currents can be found from the tests described in the last section of this procedure.

> CAUTION
>
> 1. These methods verify the continuity but not the ampacity of a grounding system.
>
> 2. Ground beds may be shock hazards; check for voltage between the ground bed and a stake driven in the earth 3 ft from the bed before proceeding with any other measurements.

The degree of safety of a grounding system is usually assessed by a measurement of its ground-bed resistance. An alternative technique of directly measuring shock potentials is presented here. Each technique has its merits. The following guidelines should help determine which is more suitable for a particular mining application.

Touch-potential measurement is recommended when--

1. It is physically impossible to disconnect the ground bed.
2. The power system cannot be shut down without severe economic penalties.

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3. Ground faults could reasonable be expected to occur near the ground bed or near equipment grounded by the bed.
4. The "footprint" of grounded equipment is comparable to the size of the ground bed. ("Footprint" here is defined as the outline of the part of the machine in contact with the earth.)
5. The grounding system is not well documented and mostly hidden from view.

Ground-bed resistance measurement is recommended when--

1. The ground bed is relatively small and conveniently disconnected.
2. The quantity or type of equipment to be grounded to the bed changes frequently.
3. Equipment connected to the bed changes location significantly between measurements.
4. Ground faults are very unlikely to occur near the ground bed or grounded equipment.

If a particular power system is better characterized by the first list above than by the latter one, the procedure explained here should be applicable.

## INSTRUMENT SELECTION

It is recommended that a commercial meter built for making ground-bed resistance measurements be used for the touch potential measurement. Any four-terminal meter built for this purpose will be suitable provided that (1) it uses a measurement frequency less than 500 Hz; (2) it produces an open-circuit voltage (between the current terminals) of less than 100 V; (3) it works reliably with up to 10 A of stray ac or dc current. The first condition assures that the measurement will be relevant to the power-frequency operation of the power system; the second makes sure that the instrument itself will not be a source of electrical shocks; and the last condition insures good measurements in the electrically hostile mining environment.

## OVERVIEW OF METHOD

Figure 3-1 shows the basic schematic of the method. Essentially, a low-level fault (typically 10 to 20 mA) is staged using the internal current source of the test instrument. Touch potential due to this fault is measured by the voltage detector of the same unit. The instrument meter displays touch potential in volts per ampere of fault current. This number must be multiplied by the largest anticipated ground-fault current to obtain the worst-case touch potential. For example, if the instrument indicateed 0.100 on a system where the maximum ground-fault current was expected to be 250 A, the maximum touch potential would be 25 V.

The instrument connections are much like those of the fall-of-potential measurement; personnel familiar with this technique should have little difficulty with measuring touch potentials. One current connection and one voltage connection are made to the ground bed (or grounded equipment) under test, and the second current and voltage connections are made to test electrodes away from the bed (or grounded equipment).

Differences between the fall-of-potential method and the touch potential method lie in the locations of these last two electrodes. In the fall-of-potential method, the current electrode is located as far as possible from the ground bed, and the potential electrode is placed at various locations on a line between the ground bed with the current electrode. In the touch-potential measurement, the potential electrode is placed 3 ft from the ground bed, and the current electrode is located where a ground fault may occur.

## GENERAL GUIDELINES FOR ELECTRODE PLACEMENT

As explained above, one current connection is always made to the ground bed. This connection is either made directly, if the test is performed near the bed, or indirectly, if the measurement is done at a piece of grounded equipment. The indirect connection is accomplished by attaching the test lead to the metal frame of the grounded equipment; this establishes electrical continuity to the ground bed through the ground wire.

Only voltage connection is also made to the ground bed, indirectly or directly

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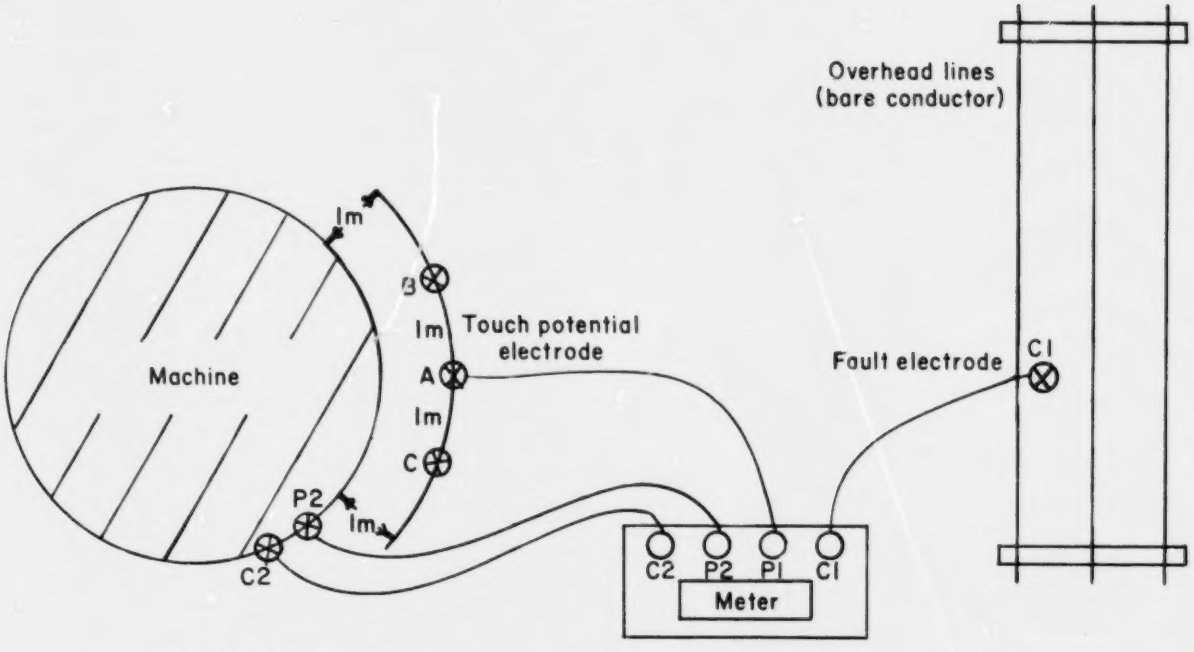


FIGURE 3-1. - Measuring touch potential at a machine with a circular footprint.

(as above). It is important that this be a separate wire from the meter to the bed or to the grounded equipment, not a jumper between the two meter terminals. A separate clamp should be provided for each connection.

The second current connection should be made to a test stake driven into the ground, at the closest point to the ground bed or any grounded equipment where a bare phase conductor could come into contact with the earth. If overhead lines pass close to remote grounded equipment, as well as close to the substation where the ground bed is built, the procedure should be performed in both places, even if the distance from the remote-grounded equipment to the overhead line is larger than the distance from the ground bed to the nearest phase-conductor grounding point.[8]

The second potential connection is also made to a test stake or electrode. Placement of this test electrode is the most difficult part of the measurement procedure. It must be placed 3 ft from grounded equipment at the point which will produce the maximum instrument reading (the maximum voltage for a given fault current). This location is not always obvious, but time spent checking different locations the first time the measurement procedure is conducted at a given mine site should not have to be repeated during subsequent tests.

The following subsections list some general guidelines depending on the type of footprint. Another section of this paper presents some specific suggestions for different mine types. However, these guidelines and suggestions are not a substitute for experience. Any incidence at a mining property of metal objects being "live" should be investigated using this procedure, by placing the potential connection at that site.

[8]In some instances, the overhead line passing by remote grounded equipment may be a high-voltage transmission or subtransmission line. A ground fault on one of these high-voltage lines may produce shock hazards that cannot be eliminated even by well-engineered ground beds. This procedure will nonetheless help quantify these hazards.

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## Machine With a Circular Footprint

When the touch potential is to be measured near a ground bed or a grounded machine that has a circular footprint, the potential electrode should be placed as close as possible to the current electrode (while maintaining the 3-ft spacing from the edge of the equipment). The most common example of this would be a dragline. Note that the 3-ft spacing should be measured along the ground from the outermost point on the dragline which a person could be expected to touch, not from the edge of the tub. The specific steps to be carried out are listed below.

1. Connect one potential lead (P2) and one current lead (C2) of the resistivity meter directly to the machine or object to be tested, as shown in figure 3-1.
2. Locate the fault current electrode (C1) at the point closest to the machine where a bare phase conductor is likely to come in contact with the earth.
3. Locate the touch potential electrode (P1) 3 ft from the farthest projection on the machine that a person can touch from the ground and directly between the machine and the fault electrode (position A). Record the instrument reading.
4. Relocate the touch potential electrode (P1) 3 ft to either side of position A (positions B and C), and record the instrument readings there. If the readings at B and C are less than at A, then A is the location of maximum touch potential.
5. If either B or C has a higher reading than A, then take an additional reading 1 m from the electrode with the higher reading, on the side of the electrode opposite location A.
6. If the reading at this fourth location is less than at location B or C (depending on which was higher than A), then B or C (again, depending on which was higher than A) is the location of the maximum touch potential.
7. If the reading at this fourth location is greater still, then a fifth reading 1 m beyond the fourth is required. Continue this measurement pattern until a maximum reading is obtained. The location of the maximum reading is the location where the maximum touch potential will occur.
8. Measure the two-terminal resistance between the fault electrode (C1) and the machine. Leave C2 and P2 connected to the machine and connect P1 to C1 with a jumper. Record the reading.
9. Calculate the fault current that will circulate between the fault and the machine. The fault current is equal to voltage of the phase conductor with respect to earth divided by the resistance between the fault and the machine. For example, if the (line-to-line) voltage is 7,200 V, corresponding to line-to-neutral voltage of 4,160 V, and the measured resistance is 1,230 ohms, then the fault current is 4,160/1,230 = 3.38 A.
10. The maximum touch potential that a person will experience is equal to the fault current multiplied by the maximum instrument reading obtained in steps 3 through 7.

## Machine With a Square Footprint

If the touch potential is to be measured near an object with a square footprint, the potential electrode should be placed in at least two different locations. First, it should be positioned as above, closest to the current electrode but still 3 ft from the edge of the object. Next, the potential electrode P1 should be placed 3 ft diagonally off the corner closest to the current electrode C1. If these first two potential-electrode positions are more than 3 ft apart, then the touch potential should be measured in a third position, halfway between the first two locations. If this third position yields the highest instrument reading, then additional positions in the vicinity of this third location should be probed until the maximum is found.

### Fault Adjacent to Side of Square

If the likely fault location is off the side of the square, the steps outlined below are appropriate.

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1. Connect one potential lead (P2) and one current lead (C2) of the resistivity meter directly to the machine or object to be tested, as shown in figure 3-2.
2. Locate the fault current electrode (C1) at the point closest to the machine where a bare phase conductor is likely to come in contact with the earth.
3. Several locations for touch potential measurements need to be investigated. Place the touch potential electrode (P1) at these locations:
   A. One meter from the machine directly between the machine and the fault electrode (point A).
   B. One meter from the machine at the center of the side closest to the fault electrode (point B).
   C. One meter from the machine at the two corners closest to the fault electrode (points C and D).

Make a measurement at each of these locations and find the location that gives the maximum reading.

4. Take additional measurements 1 m on either side of the maximum reading found in step 3. If these lateral measurements are less than the central measurement, then the central location is where the maximum touch potential will occur.
5. If either of the lateral readings is higher than the central reading, then another measurement needs to be taken 1 m beyond the higher lateral reading. Continue this measurement pattern until a maximum reading is found.
6. Measure the two-terminal resistance between the fault electrode (C1) and the machine. Leave C2 and P2 connected to the machine and connect P1 to C1. Record the reading.
7. Calculate the fault current that will circulate between the fault and the machine. The fault current is equal to the voltage of the phase conductor with respect to earth divided by the resistance between the fault and the machine.
8. The maximum touch potential that a person will experience is equal to the fault current multiplied by the maximum instrument reading obtained in steps 3 through 5.

Fault Adjacent to Corner of Square

If the likely fault location is off a corner of the square, then the procedure shown next is appropriate.

1. Connect one potential lead (P2) and one current lead (C2) of the resistivity meter directly to the machine or object to be tested, as shown in figure 3-3.
2. Locate the fault current electrode (C1) at the point closest to the machine where a bare phase conductor is likely to come in contact with the earth.
3. Locate the touch potential electrode (P1) at these points near the machine:
   A. One meter from the corner nearest the fault electrode (point A).
   B. One meter from the midpoints of the two sides nearest the fault electrode (points B and C).

Make measurements at these locations and find the location that gives the maximum reading.

4. Take additional measurements 1 m on either side of the maximum reading found in step 3. If these lateral measurements are less than the central measurement, then the central location is where the maximum touch potential will occur.
5. If one of the lateral readings is higher than the central reading, then another measurement needs to be taken 1 m beyond the higher lateral reading. Continue this measurement pattern until a maximum reading is found.
6. Measure the two-terminal resistance between the fault electrode (C1) and the machine. Leave C2 and P2 connected to the machine and connect P1 to C1. Record the reading.
7. Calculate the fault current that will circulate between the fault and the machine. The fault current is equal to the voltage of the phase conductor with respect to earth divided by the resistance between the fault and the machine.
8. The maximum touch potential that a person will experience is equal to the fault current multiplied by the maximum instrument reading obtained in steps 3 through 5.

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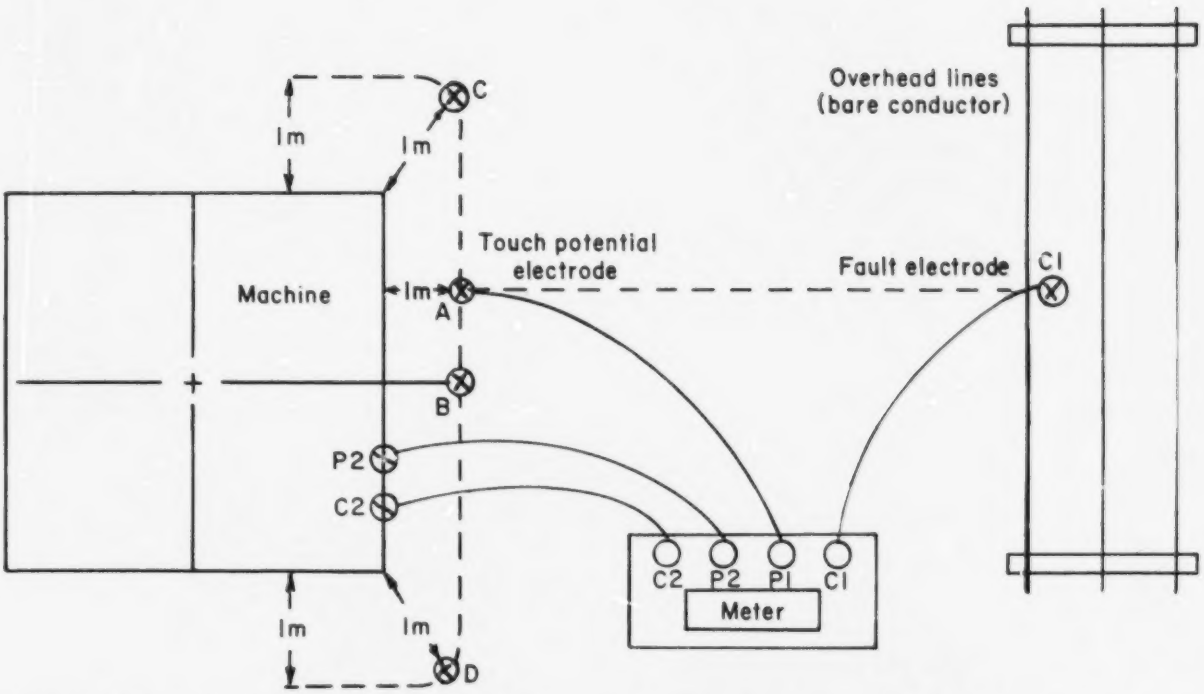


FIGURE 3-2. - Measuring touch potential at a machine with a square footprint, fault nearest one side.

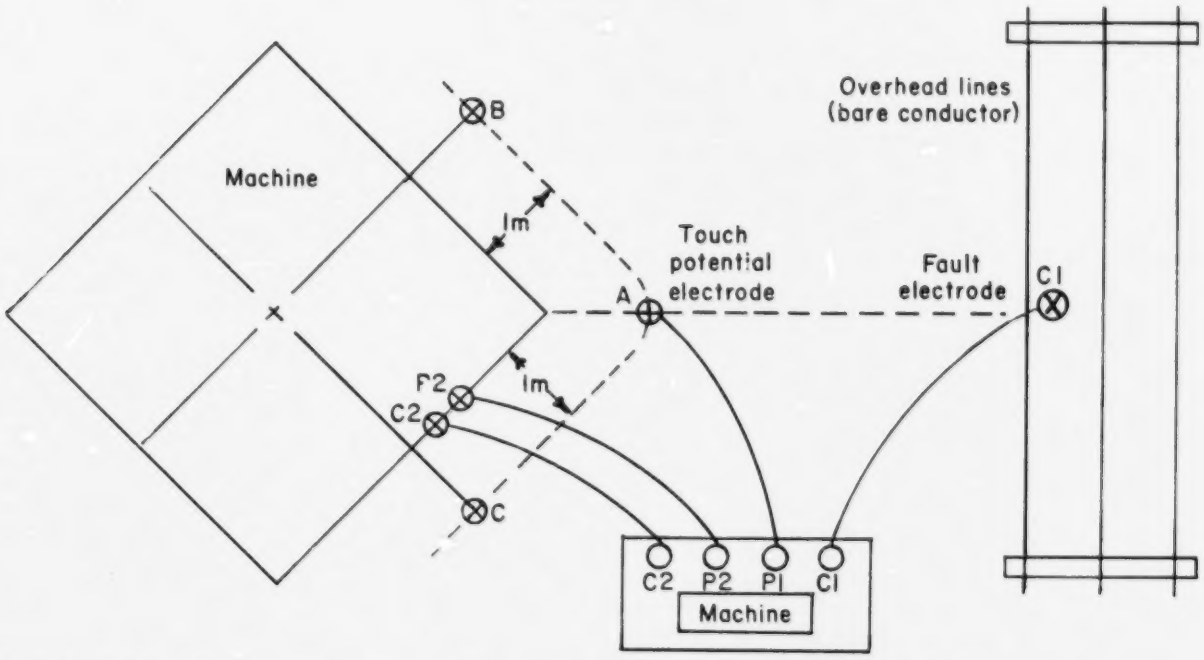


FIGURE 3-3. - Measuring touch potential at a machine with a square footprint, fault nearest one corner.

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Machine With a Rectangular Footprint

If the object has a rectangular footprint, two more potential-electrode positions should be added: 3 ft off the middle of a short side of the object, and 3 ft off the long side of the object. The short side and the long side chosen should be the closer ones to the current electrode. As above, measurements should be made at intermediate positions between these initial positions until the maximum instrument reading is obtained.

Fault Adjacent to Long Side of Rectangle

If the likely fault location is off the long side of the rectangle, follow the steps below.

1. Connect one potential lead (P2) and one current lead (C2) of the resistivity meter directly to the machine or object to be tested, as shown in figure 3-4.
2. Locate the fault current electrode (C1) at the point closest to the machine where a bare phase conductor is likely to come in contact with the earth.
3. Several locations for touch potential measurements need to be investigated. Place the touch potential (P1) at these locations:
   A. One meter from the machine directly between the machine and the fault electrode (point A).
   B. One meter from the machine at the center of the side closest to the fault electrode (point B).
   C. One meter from the machine at the two corners closest to the fault electrode (points C and D).
   D. One meter from the machine at the center of the short side closest to the fault electrode (point E).

Make measurements at these locations and find the location which gives the maximum reading.

4. Take additional measurements 1 m on either side of the maximum reading found in step 3. If these lateral measurements are less than the central measurement, then the central location is where the maximum touch potential will occur.
5. If one of the lateral readings is higher than the central reading, then another measurement needs to be taken 1 m beyond the higher lateral reading. Continue this measurement pattern until a maximum reading is found.
6. Measure the two-terminal resistance between electrode (C1) and the machine. Leave C2 and P2 connected to the machine and connect P1 to C1. Record the reading.
7. Calculate the fault current that will circulate between the fault and the machine. The fault current is equal to the voltage of the phase conductor with respect to earth divided by the resistance between the fault and the machine.
8. The maximum touch potential that a person will experience is equal to the fault current multiplied by the maximum instrument reading obtained in steps 3 through 5.

Fault Adjacent to Short Side of Rectangle

If the likely fault location is off the short side of the rectangle, the steps outlined below are appropriate.

1. Connect one potential lead (P2) and one current lead (C2) of the resistivity meter directly to the machine or object to be tested, as shown in figure 3-5.
2. Locate the fault current electrode (C1) at the point closest to the machine where a bare phase conductor is likely to come in contact with the earth.
3. Several locations for touch potential measurements need to be investigated. Place the touch potential electrode (P1) at these locations:
   A. One meter from the machine directly between the machine and the fault electrode (point A).
   B. One meter from the machine at the center of the side closest to fault electrode (point B).
   C. One meter from the machine at the two corners closest to the fault electrode (points C and D).

Make measurements at these locations and find the location that gives the maximum reading.

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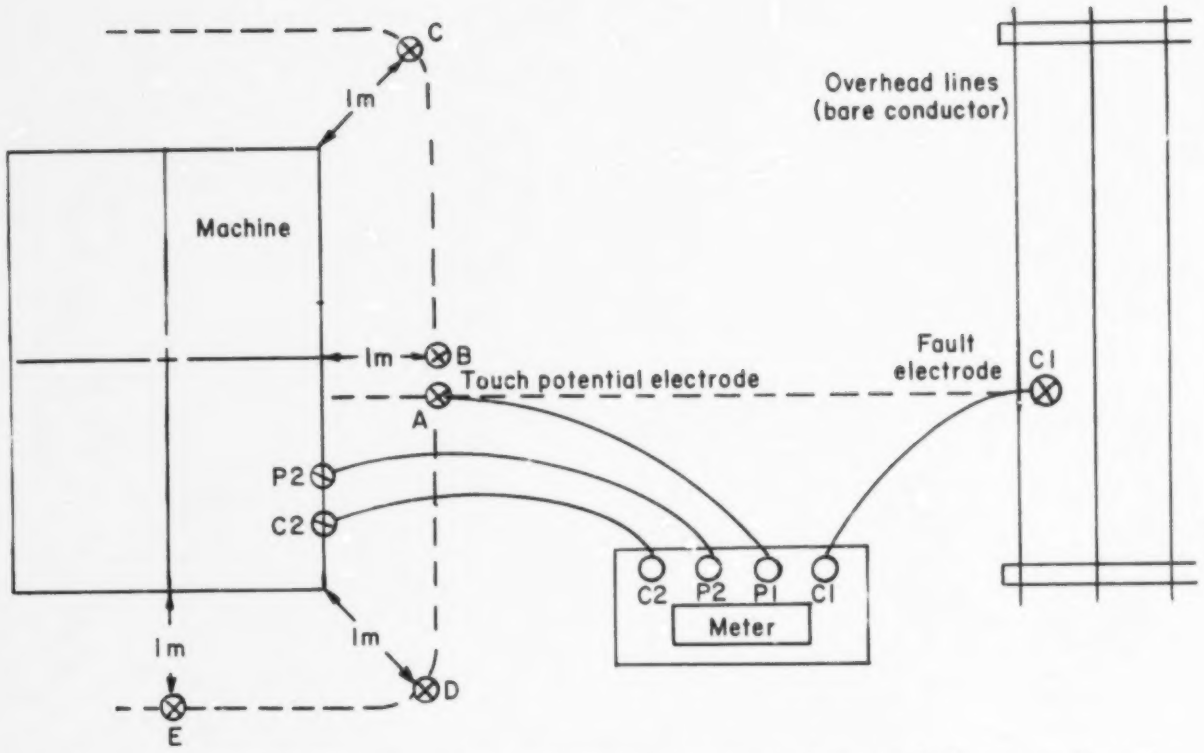


FIGURE 3-4. - Measuring touch potential at a machine with a rectangular footprint, fault nearest a long side.

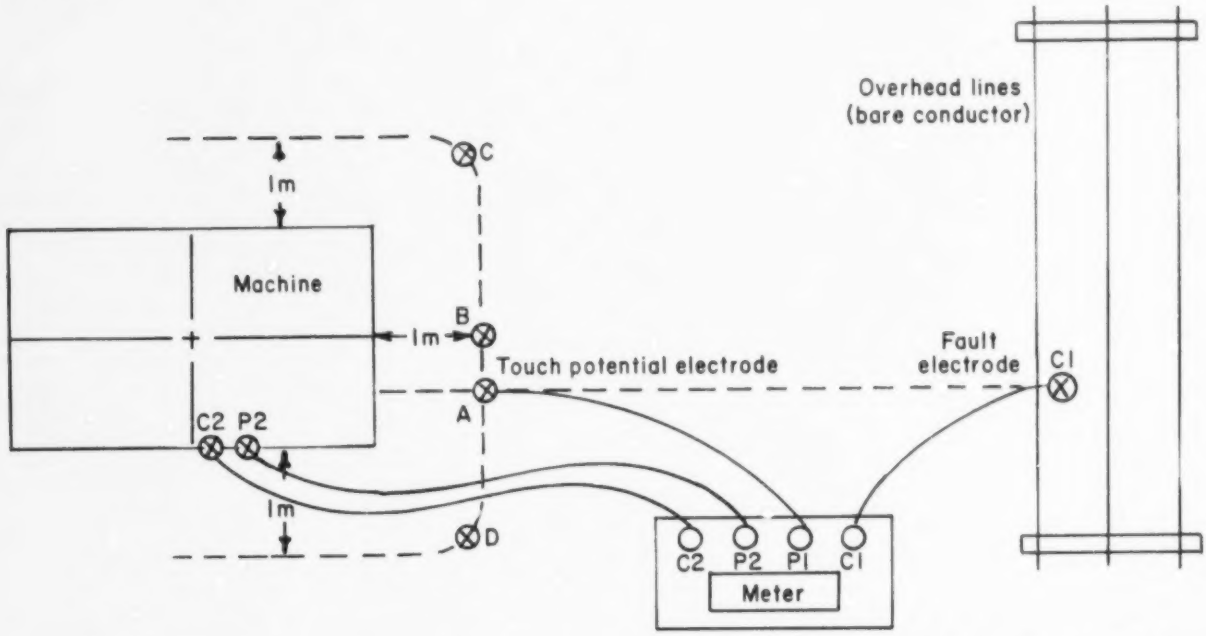


FIGURE 3-5. - Measuring touch potential at a machine with a rectangular footprint, fault nearest a short side.

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4. Take additional measurements 1 m on either side of the maximum reading found in step 3. If these lateral measurements are less than the central measurement, then the central location is where the maximum touch potential will occur.

5. If one of the lateral readings is higher than the central reading, then another measurement needs to be taken 1 m beyond the higher lateral reading. Continue this measurement pattern until a maximum reading is found.

6. Measure the two-terminal resistance between electrode (C1) and the machine. Leave C2 and P2 connected to the machine and connect P1 to C1. Record the reading.

7. Calculate the fault current that will circulate between the fault and the machine. The fault current is equal to the voltage of the phase conductor with respect to earth divided by the resistance between the fault and the machine.

8. The maximum touch potential that a person will experience is equal to the fault current multiplied by the maximum instrument reading obtained in steps 3 through 5.

Fault Adjacent to Corner of Rectangle

If the likely fault location is off the corner of the rectangle, the steps outlined below are appropriate.

1. Connect one potential lead (P2) and one current lead (C2) of the resistivity meter directly to the machine or object to be tested as shown in figure 3-6.

2. Locate the fault current electrode (C1) at the point closest to the machine where a bare phase conductor is likely to come in contact with earth.

3. Locate the touch potential electrode (P1) at these points near the machine:

   A. One meter from the corner nearest the fault electrode (point A).

   B. One meter from the midpoints of the two sides nearest the fault electrode (points B and C).

Make measurements at these locations and find the location which gives the maximum reading.

4. Take additional measurements 1 m on either side of the maximum reading found in step 3. If these lateral measurements are less than the central measurement, then the central location is where the maximum touch potential will occur.

5. If one of the lateral readings is higher than the central reading, then another measurement needs to be taken 1 m beyond the higher lateral reading. Continue this measurement pattern until a maximum reading is found.

6. Measure the two-terminal resistance between electrode (C1) and the machine. Leave C2 and P2 connected to the machine and connect P1 to C1. Record the reading.

7. Calculate the fault current that will circulate between the fault and the machine. The fault current is equal to the voltage of the phase conductor with respect to earth divided by the resistance between the fault and the machine.

8. The maximum touch potential that a person will experience is equal to the fault current multiplied by the maximum instrument reading obtained in steps 3 through 5.

Machine With an Irregular Footprint

Irregularly shaped objects provide the greatest challenge. If the object has a shape which can be approximated by those discussed above, then the recommendations for that shape can be followed. Special attention should be given to narrow extensions of the object footprint, such as outriggers on drills, dragline buckets, and conveyor belts. Measurements should be made off the ends of these extensions, beginning with those which are closest to the current electrode C1. It may be necessary to consider several current-electrode positions if the object is large and ground faults could occur at different points near the object. The potential electrode should be placed 3 ft from the end of any extension, regardless of whether the extension is in contact with the earth, as long as a person could stand on earth and touch the extension. The specific steps to be carried out are listed below.

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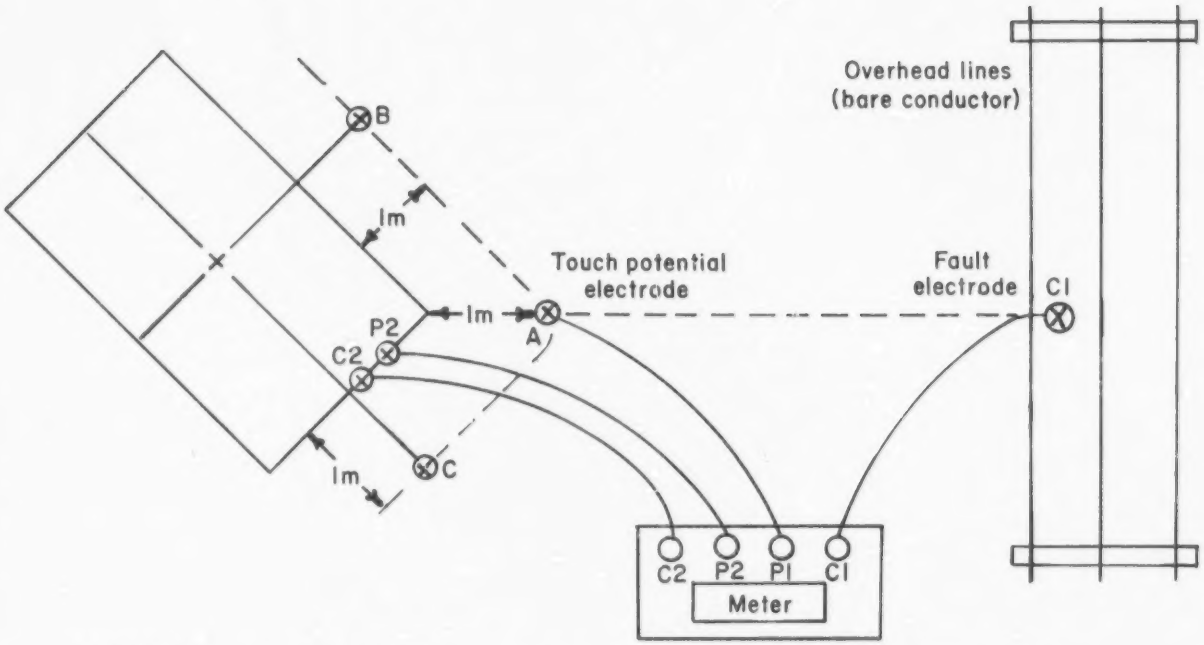


FIGURE 3-6. - Measuring touch potential at a machine with a rectangular footprint, fault nearest one corner.

1. Connect one potential lead (P2) and one current lead (C2) of the resistivity meter directly to the machine or object to be tested.

2. Locate the fault current electrode (C1) at the point closest to the machine where a bare phase conductor is likely to come in contact with the earth.

3. Locate the touch potential electrode (P1) at these points near the machine:

A. One meter from the machine directly between the machine and the fault electrode (point A).

B. One meter from the machine at all narrow projections or extensions.

C. One meter from the machine at the center of the narrow sides of machine nearest the fault electrode.

Make measurements at these locations and find the location that gives the maximum reading.

4. Take additional measurements 1 m on either side of the maximum reading found in step 3. If these lateral measurements are less than the central measurement, then the central location is where the maximum touch potential will occur.

5. If one of the lateral readings is higher than the central reading, then another measurement needs to be taken 1 m beyond the higher lateral reading. Continue this measurement pattern until a maximum reading is found.

6. Measure the two-terminal resistance between electrode (C1) and the machine. Leave C2 and P2 connected to the machine and connect P1 to C1. Record the reading.

7. Calculate the fault current that will circulate between the fault and the machine. The fault current is equal to the voltage of the phase conductor with respect to earth divided by the resistance between the fault and the machine.

8. The maximum touch potential that a person will experience is equal to the fault current multiplied by the maximum instrument reading obtained in steps 3 through 5.

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## SPECIFIC RECOMMENDATIONS FOR SELECTED MINE TYPES

### Separate Ground Beds

An additional test should be performed at mines that follow the practice (required in coal mines) of having two separate ground beds. The current electrode should be placed to simulate a ground fault as close as conceivable to the station ground, and the touch potentials measured at the safety ground. The potential electrode should be positioned as above, close to the current electrode, but 3 ft from the bed. This test will evaluate the effectiveness of ground-bed separation. Ground faults near the safety ground bed should be probed as outlined in the section, "General Guidelines for Electrode Placement," treating the bed as a "machine" with the same footprint as the bed.

### Dredging Operations

Although a dredge is surrounded by water, it is treated like any other machine in the touch-potential measurement (although the potential probe has to be located in the water). Special attention should be given to the side of the dredge where personnel get on or off, but highest touch potentials will usually be encountered on the side of the dredge closest to the shore power feed. The current probe should be positioned for the closest ground fault to the dredge. This may be at a cable coupler close to the dredge, in addition to the usual overhead line locations.

### Open-Pit Mines

For mines with ring feeds, care should be taken to ensure that the closest possible ground fault be used when checking for touch potentials on pit equipment. An overhead line does not have to feed a particular machine to cause a shock hazard at the machine when it is downed.

### Underground Mines

It is not practical to check touch potentials on underground machinery due to a surface ground fault. Measurements will have to be made at the ground bed on the surface.

## DETERMINATION OF FAULT-CURRENT VALUES

The instrument readings obtained from the procedures previously outlined determine maximum values of mutual resistances; that is, touch potentials per ampere of fault current. Values of maximum ground-fault current must be found to convert these instrument readings into touch potentials. There are three principal sources of these maximum currents: (1) engineering estimates from line impedance and assumed fault impedance; (2) staged-fault tests; and (3) the experimental approach explained below. Of the three methods, the first is the most approximate, as it requires assuming a value for the ground-fault impedance. Because this impedance is a critical parameter in the calculation, large errors can be introduced.

Staged-fault tests produce much more reliable numbers, but the potential danger to personnel and the electrical stress on equipment make this an unattractive alternative. Also, variations in earth resistivity and the length of phase conductor in contact with the earth produce a wide range of fault currents. However, for overhead lines above 15 kV, there is no alternative.

The experimental approach is to experimentally measure the resistance seen by the faulted phase. Dividing the line-to-neutral voltage by this resistance produces an estimate of the ground-fault current. This approach works if the ground-fault resistance is much larger than the source impedance (usually true) and the line voltage is low enough so that ionization of the earth is not appreciable (usually true for 15 kV or less). Merits of this method are that

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situations, such as phase conductors falling on ungrounded metal objects, can be explicitly considered.

Figure 3-7 illustrates the procedure. A current is circulated between the system neutral and an electrode corresponding to the downed phase conductor. This electrode may be a length of bare conductor on the ground, representing the phase conductor, or may be a metal object onto which a phase conductor could fall. (The chosen object should not be connected to the grounding system, as this would not produce substantial fault current through-the-earth; the fault would be line-to-neutral.) The ground fault should be located at the worst-case position of the current electrode, determined above. Note that the grounding resistor, if present, would be correctly included in the ground-fault resistance.

The resistance measured above should be divided into the highest line-to-neutral voltage expected on a continuous basis. Because the measured resistance is a low estimate of the fault impedance, the fault current calculated will be a conservative (high) estimate of the maximum fault current. This estimated current may be unreasonably high if the measured resistance is very low, owing to the neglected impedance of the transmission and distribution system.

## INTERPRETATION OF RESULTS

The maximum instrument reading obtained previously, multiplied by the maximum ground-fault current, yields the worst-case touch potential. If the maximum fault current was found from the experimental procedure of the last section, the results should be reviewed to verify that the ground-fault resistance was measured at the same location as the current electrode was placed for the original test.

Touch potentials of 100 V or more are unacceptable. If the tests reveal values close to, but less than, 100 V, the test procedure should be reviewed and additional measurements should be taken to ensure that the worst-case values have indeed been found. Values approaching 100 V can be lethal in a wet or otherwise low-resistivity area.

## MITIGATION OF TOUCH-POTENTIAL HAZARDS

Reduction of touch potentials, or reducing the hazards due to these potentials, cannot be fully treated here. Listed below are some methods of attacking the problem. In general, the hazard is reduced by decreasing the ground-fault current, by decreasing the mutual resistance (voltage per ampere of fault current), or else by keeping personnel away from an area of high potentials.

Touch potentials can be reduced by increasing the separation of overhead lines and equipment (or ground beds) from possible ground-fault locations. Moving either the overhead line or the equipment will reduce the hazard. If the high touch potential is confined to a small area, such as the dragline bucket near an overhead line, keeping personnel away from the area may be effective. Adding additional rods to narrow sides of ground beds will reduce touch potentials near

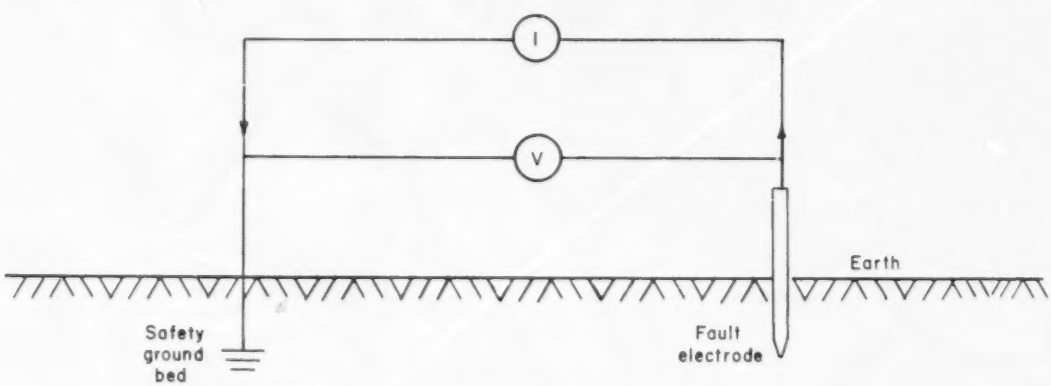


FIGURE 3-7. - Determination of expected fault current.

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these sides. Reducing ground-fault current, by moving metal objects out of the right-of-way of distribution lines (to increase the ground-fault impedance), by increasing grounding-resistor value (to increase the resistance in series with the fault), or by placing gravel in low-resistivity areas under lines (to increase ground-fault impedance) will also decrease touch potentials.

If these techniques do not reduce the hazards sufficiently, redesign of the grounding system may be necessary. Separation of grounds may be advantageous; in some cases, the opposite procedure of combining separate ground beds (if permitted) may provide relief.

## CONCLUSION

In this paper a new method to assess earth grounding safety has been fully documented in cookbook format. Since a commercially available meter is employed, the procedure can be readily adopted by the Mine Safety and Health Administration (MSHA) and the mining industry.

## REFERENCES

1. American Standards Association, American Mining Congress, and U.S. Bureau of Mines. American Standard Safety Rules for Installing and Using Electrical Equipment in and About Coal Mines. BuMines IC 8227, 1964, 27 pp.

2. Lordi, A. C. How To Safely Ground Mine Power Systems. Coal Age, v. 68, Sept. 1963, pp. 110-117.

3. King, R. L., H. W. Hill, Jr., R. R. Bafana, and W. L. Cooley. Guide for the Construction of Driven-Rod Ground Beds. BuMines IC 8767, 1978, 26 pp.

4. Cooley, W. L., and R. L. King. Guide to Substation Grounding and Bonding for Mine Power Systems. BuMines IC 8835, 1980, 27 pp.

5. Mitchell, J. B., H. W. Hill, Jr., and W. L. Cooley. Composite Material Ground Beds for Difficult Areas. Paper in Proceedings of the Fifth WVU Conference on Coal Mine Electrotechnology, July 30-31, August 1, 1980, ed. by N. S. Smith. BuMines OFR 82-81, 1980, pp. 10-1 to 10-18.

6. Mitchell, J. B. Composite Material Ground Beds for Low-Conductivity Soils. M.S. Thesis, WV Univ., 1981, 103.

7. Sunde, E. D. Earth Conduction Effects in Transmission Systems. Dover Publ. Inc., 1967, 370 pp.

8. James G. Biddle Co. Getting Down to Earth. Plymouth Meeting, PA, 1970, 48 pp.

9. Hill, H. W., Jr. Private communication, 1985; available upon request from M. R. Yenchek, BuMines, Pittsburgh, PA.

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